Environmental Research 173 (2019) 255–261

Contents lists available at ScienceDirect

Environmental Research

journal homepage: www.elsevier.com/locate/envres

The impact of climate variability on infectious disease transmission in China: Current knowledge and further directions

Liping Yi[a,1], Xin Xu[b,1], Wenxin Ge[a,1], Haibin Xue[c], Jin Li[d], Daoyuan Li[e], Chunping Wang[a], Haixia Wu[f], Xiaobo Liu[f], Dashan Zheng[a], Zhe Chen[a], Qiyong Liu[f], Peng Bi[g,h,**], Jing Li[a,i,*]

[a] Division of Environmental Health, School of Public Health and Management, Weifang Medical University, Weifang, 261053, Shandong Province, PR China
[b] Department of Dentistry, Affiliated Hospital, Weifang Medical University, Weifang, 261053, Shandong Province, PR China
[c] Clinical Laboratory, Weifang People's Hospital, Weifang, 261000. Shandong Province, PR China
[d] Department of Dentistry, Weifang People's Hospital, Weifang, 261000, Shandong Province, PR China
[e] Department of Emergency, Weifang No.2 People's Hospital, Weifang, 261041, Shandong Province, PR China
[f] State Key Laboratory of Infectious Disease Prevention and Control, National Institute for Communicable Disease Control and Prevention, Chinese Center for Disease Control and Prevention, Beijing, 102206, PR China
[g] School of Public Health, The University of Adelaide, Adelaide, SA 5005, Australia
[h] School of Public Health, Anhui Medical University, Hefei, 230032, Anhui Province, PR China
[i] "Health Shandong" Major Social Risk Prediction and Governance Collaborative Innovation Center, Weifang, 261053, Shandong Province, PR China

ARTICLE INFO

Keywords:
Climate change
Infectious disease
Health burden
China

ABSTRACT

Background: Climate change may lead to emerging and re-emerging infectious diseases and pose public health challenges to human health and the already overloaded healthcare system. It is therefore important to review current knowledge and identify further directions in China, the largest developing country in the world.

Methods: A comprehensive literature review was conducted to examine the relationship between climate variability and infectious disease transmission in China in the new millennium. Literature was identified using the following MeSH terms and keywords: climatic variables [temperature, precipitation, rainfall, humidity, etc.] and infectious disease [viral, bacterial and parasitic diseases].

Results: Fifty-eight articles published from January 1, 2000 to May 30, 2018 were included in the final analysis, including bacterial diarrhea, dengue, malaria, Japanese encephalitis, HFRS, HFMD, Schistosomiasis. Each 1 °C rise may lead to 3.6%–14.8% increase in the incidence of bacillary dysentery disease in south China. A 1 °C rise was corresponded to an increase of 1.8%–5.9% in the weekly notified HFMD cases in west China. Each 1 °C rise of temperature, 1% rise in relative humidity and one hour rise in sunshine led to an increase of 0.90%, 3.99% and 0.68% in the monthly malaria cases, respectively. Climate change with the increased temperature and irregular patterns of rainfall may affect the pathogen reproduction rate, their spread and geographical distribution, change human behavior and influence the ecology of vectors, and increase the rate of disease transmission in different regions of China.

Conclusion: Exploring relevant adaptation strategies and the health burden of climate change will assist public health authorities to develop an early warning system and protect China's population health, especially in the new 1.5 °C scenario of the newly released IPCC special report.

Abbreviations: WHO, World Health Organization; JE, Japanese encephalitis; HFMD, Hand, foot and mouth disease; HFRS, Hemorrhagic fever with renal syndrome; DF, Dengue fever; BD, Bacterial dysentery; DLNM, The distributed lag non-linear model; SARIMA, The seasonal autoregressive integrated moving average model; GEE, Generalized estimating equation models; GAM, Generalized Additive Models; GLM, Generalized Linear Models; GIS, Geographic Information System; ENM, ecological niche modeling; SOI, Southern Oscillation Index; ZIPR model, Zero-Inflated Poisson Regression models; ARIMA, Autoregressive integrated moving average model; PCA, Principle Component Analysis; RR, relative risk; CI, confidence interval; *P. vivax*, *Plasmodium vivax*; *O. hupensis*, *Oncomelania hupensis*

* Corresponding author. Division of Environmental Health, School of Public Health and Management, Weifang Medical University, Address: No. 7166 Baotong Xi Street, Weifang, 261053, Shandong Province, PR China.
** Corresponding author. School of Public Health, the University of Adelaide. Address: The University of Adelaide, Adelaide, SA 5000, Australia.
E-mail addresses: Peng.bi@adelaide.edu.au (P. Bi), lijingsddx@126.com (J. Li).
[1] Co-first authors.

https://doi.org/10.1016/j.envres.2019.03.043
Received 30 October 2018; Received in revised form 20 January 2019; Accepted 17 March 2019
Available online 20 March 2019
0013-9351/ © 2019 Elsevier Inc. All rights reserved.

1. Introduction

Climate change, with the changes in temperature and precipitation, and increasing extreme weather events, has and will continue to impact the transmission of infectious diseases via affecting pathogen growth and development, survival of vector and human behavior (Shuman, 2011). World Health Organization (WHO) projected that, 10% of diarrheal diseases will increase by 2030 due to climate change (Shuman, 2011; World Health Organization, 2010). If global temperatures continue to increase by 2 °C–3 °C, the population at risk for malaria will increase by 3%–5% (Shuman, 2011; World Health Organization, 2010). With 34 provincial jurisdictions and a total of 1.39 billion populations, China is a major contributor to global infectious disease burden (Kan et al., 2012; National Bureau of Statistics, 2017). Over the period 2009–2017, there were an average of 6,618,257 infectious disease notifications each year with the mortality rate around 1.25/100,000 (Chinese center for disease control and prevention, 2018). Among the notifiable infectious diseases in China, plague, cholera, malaria, dengue fever, Japanese encephalitis, typhoid fever and paratyphoid fever, hand, foot and mouth disease, bacterial dysentery, epidemic hemorrhagic fever and schistosomiasis are climate sensitive. Given the current very low incidence of plague, cholera, typhoid and paratyphoid in China, this paper will focus on the seven infectious diseases with public health significance, examine the impact of climate variability on the transmission of these diseases, discuss the research limitations, and suggest further research directions and government actions to be established in China.

2. Methods

2.1. Search strategy

Several mainstream databases including the Web of Science, PubMed, CNKI (http://www.cnki.net/) were used to search original literature. To expand the search scope, we used series of key word combinations to conduct the search. More details are listed in Table 1.

2.2. Inclusion and exclusion criteria

In this paper, studies published both in English and Chinese about climate change and infectious diseases in China were referenced. Fig. 1 shows the process of search and inclusion/exclusion.

Literature were included according to following rules:

1. Studies must examine the association between climate variability/change and infectious disease. Those analyzing the etiology, diagnosis and treatment of communicable disease were excluded.
2. Only the studies published from January 1, 2000 to May 30, 2018 and conducted in China were included.
3. Papers focusing on the seven infectious diseases with public health significance in China (Table 2) were included. Those discussing other diseases were excluded.

Among all related literature, fifty-eight articles finally met the inclusion criteria.

Table 1
Key terms used for searching.

Infectious disease	Climatic variables
Communicable disease	Climate variability
Infectious disease	Climate change
Viral infectious diseases	Meteorological variables
DF	Global warming
HFRS	Temperature
HFMD	Precipitation
JE	Rainfall
Bacterial infectious diseases	Humidity
Dysentery	Extreme weather
Parasitic diseases	Heat waves
Malaria	Floods
Schistosomiasis	Droughts
	Typhoons

*DF: Dengue fever; HFRS: Hemorrhagic fever with renal syndrome; HFMD: Hand, foot and mouth disease; JE: Japanese encephalitis.

3. Results and discussion

3.1. Infectious diseases under investigation

Climate change affects infectious disease via its impacts on pathogen, host and transmission environment (Liang and Gong, 2017). In this review, we assess its impacts on seven pathogenic diseases with significant public health challenges in China, namely viral infectious diseases, bacterial infectious diseases and parasitic diseases. Table 2 shows the papers categorized by disease nature (Heaney et al., 2016).

3.2. Research approaches in the literature

Most of the published studies used ecological study design for the risk assessments. In terms of time-series data analyses, various statistical methods and mathematical models were implemented. The distributed lag non-linear model (DLNM) was used to graphically demonstrate the impact of climate variability on infectious disease transmission (Guo et al., 2015; Wu et al., 2017a; Bi et al., 2013; Xiang et al., 2017; Qi et al., 2018; Wang et al., 2017; Zhu et al., 2016; Cheng et al., 2014; Zhang et al., 2015; Bai et al., 2014a). The seasonal autoregressive integrated moving average (SARIMA) model was applied to identify and quantify the relationship between the meteorological variables and disease transmission (Zhang et al., 2007, 2008, 2010; Gao et al., 2014; Huang et al., 2011; Wei et al., 2015; Yan et al., 2017). ArcGIS is an effective geographic information system working with mapping and geographic information, which has been utilized together with other statistical approach in this area to explore its temporal-spatial relationship with climate variability.

There are 13 articles exploring the relationship between infectious diseases and climate variability or extreme weather events at the national scale. Three discussed such association at a regional level such as South or North China. Research locations are shown in Fig. 2, indicating that there are still some regions in which no research was conducted.

3.3. Associations between climatic variables and infectious diseases

3.3.1. Bacterial infectious disease

3.3.1.1. Bacterial dysentery. Bacterial dysentery, also referred as bacillary dysentery, is an intestinal infectious disease caused by Shigella (Lan and Hong, 2013). It usually occurs in summer and autumn, suggesting that it may be associated with hot, humid weather conditions (Zhang et al., 2008). Studies in China suggested that bacillary dysentery could be sensitive to precipitation, ambient temperature and flood events (Gao et al., 2016). Using time series analysis, the researchers observed that the monthly incidence of dysentery was positively associated with temperature, precipitation and relative humidity, but negatively related to air pressure in Jinan (Eastern China), Shenzhen (South), Shenyang (Northeast) and Beijing (North) (Zhang et al., 2007; Li et al., 2015; Huang et al., 2008). However, another study conducted in Wuhan, central China, founded that bacillary dysentery occurrence was positively associated with mean temperature while negatively related to relative humidity and precipitation, which may be due to differences in analytical methods, economic development levels, behavioral habits or climatic characteristics (Li et al., 2013a). The temperature lag effect in southern cities was found shorter than that in northern cities

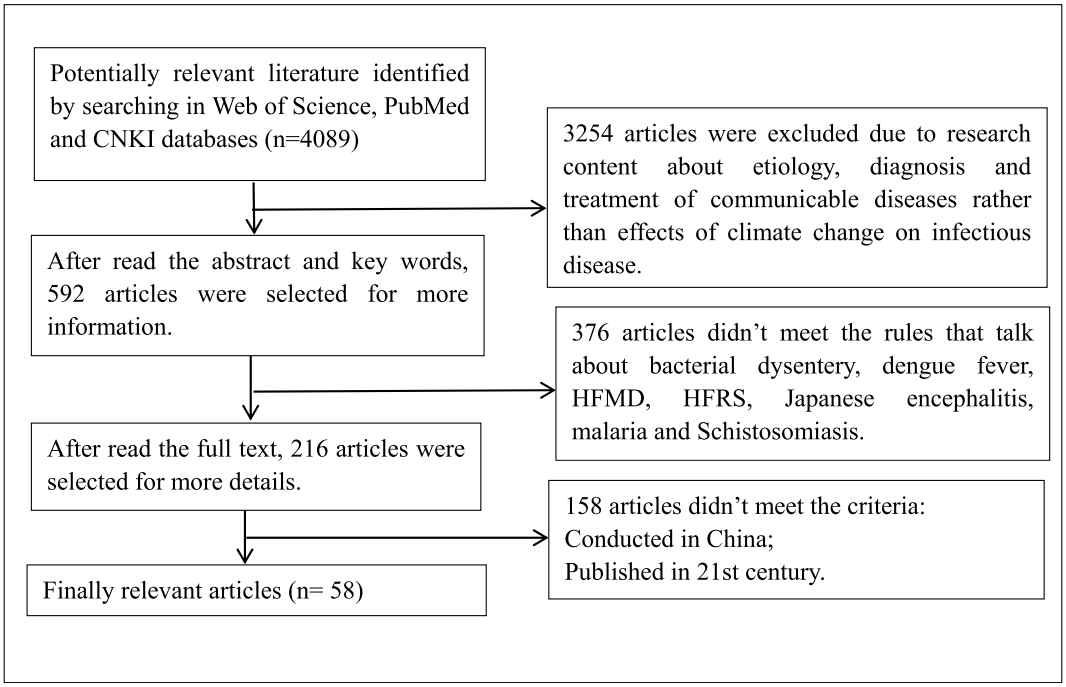
Potentially relevant literature identified by searching in Web of Science, PubMed and CNKI databases (n=4089)
3254 articles were excluded due to research content about etiology, diagnosis and treatment of communicable diseases rather than effects of climate change on infectious disease.
After read the abstract and key words, 592 articles were selected for more information.
376 articles didn't meet the rules that talk about bacterial dysentery, dengue fever, HFMD, HFRS, Japanese encephalitis, malaria and Schistosomiasis.
After read the full text, 216 articles were selected for more details.
158 articles didn't meet the criteria:
Conducted in China;
Published in 21st century.
Finally relevant articles (n= 58)

Fig. 1. Flow chart of literature search strategy.

Table 2
Papers categorized by disease topic.

Disease nature	Diseases	Numbers of papers
Viral infection	DF	10
	HFMD	10
	HFRS	5
	JE	5
Bacterial infection	Bacterial dysentery	8
Parasitic infection	Malaria	8
	Schistosomiasis	3
Others		9
Total		58

indicating that baseline temperature is relevant higher in South China and a slight increase in temperature may accelerate the pathogen growth and development (Zhang et al., 2008; Li et al., 2015). A study in Guangzhou found that each 1 °C rise of temperature was corresponded to an increase of 3.60% in the monthly notified cases, whereas 1hPa rise in atmospheric pressure corresponded to a decrease in the number of cases by 2.85% (Li et al., 2014a). Another study also conducted in South China suggested that 1 °C rise in mean temperature, mean maximum temperature (T_{max}), and mean minimum temperature (T_{min}) might lead to 14.8%, 12.9%, and 15.5% increase in the incidence of bacillary dysentery disease, respectively (Gao et al., 2014), suggesting that climate change will lead to more bacterial dysentery cases in China. It is therefore important to identify the threshold temperature and establish an early warning system (Table A.1).

3.3.2. Parasitic disease

3.3.2.1. Malaria. Malaria is a climate-sensitive vector-borne disease caused by *Plasmodium*. With effective interventions, the number of malaria cases had decreased from 24 million cases in the early 1970s to 30,000 in the late 1990s in China (Huang et al., 2017). Climatic factors can change the survival and reproduction cycle of Anopheles mosquitoes and accelerate the outer cycle of *Plasmodium* (Bai et al., 2013). It is predicted that if there are no preventive measures, the geographical scope of certain malaria vectors such as *Anopheles minimus and Anopheles dirus* will increase by 16%–49% by 2030 (Ren et al., 2016), and accordingly, the incidence of malaria may increase by 43%–73% in Huaihe River Basin (Song et al., 2016). A series of studies have found that temperature, precipitation, sunshine hours and relative humidity are closely related to the incidence of malaria (Guo et al., 2015; Li et al., 2013b), with a certain lag effect (Wu et al., 2017a; Bi et al., 2013; Xiang et al., 2018a; Gao et al., 2012), which lasts longer in the cool climate zone than that in the warm climate zone (Guo et al., 2015; Wu et al., 2017a; Bi et al., 2013; Huang et al., 2011; Xiang et al., 2018a; Gao et al., 2012). A study in Jinan, eastern China, showed that a 1 °C rise in T_{max} may be related to a 7.7%–12.7% increase in the number of malaria cases, while a 1 °C rise in T_{min} may result in approximately 11.8%–15.8% increase in cases (Zhang et al., 2010). In Tibet, west China, the incidence of malaria is mostly associated with the relative humidity which directly affects the bite and reproductive rate of mosquitoes and when the relative humidity is less than 60%, malaria transmission will be restrained (Huang et al., 2011; Xiang et al., 2018a). Bi in Yunnan and Gao in Anhui have found that precipitation factors have far more influence on malaria transmission than other weather factors (Bi et al., 2013 Gao et al., 2012). In addition, study in southern China revealed that each 1 °C rise of temperature, 1% rise in relative humidity and one hour rise in sunshine led to an increase of 0.90%, 3.99% and 0.68% in the monthly cases, respectively (Li et al.,2013b). During the flood event in 2007 in Anhui, eastern China, the most commonly notified diseases was malaria (incidence rate = 17.867/100,000) (Gao et al., 2016). Within a certain range, the rainfall provides the *Anopheles* with additional breeding sites (Bi et al., 2013; Gao et al., 2012), while heavy rain will wash away the larvae and eggs which would reduce the incidence of malaria (Wu et al., 2017a; Xiang et al., 2018a; Gao et al., 2012). Given the variations in socioeconomic status, climatic and geographic characteristics, relevant actions could be taken for China's malaria elimination program. In southwestern China, for instance, special attention should be paid to the border regions where the imported malaria cases could play an important role in the disease transmission. An integrated measurement, including vector monitoring and control, disease surveillance and weather watching should be implemented (Table A.2).

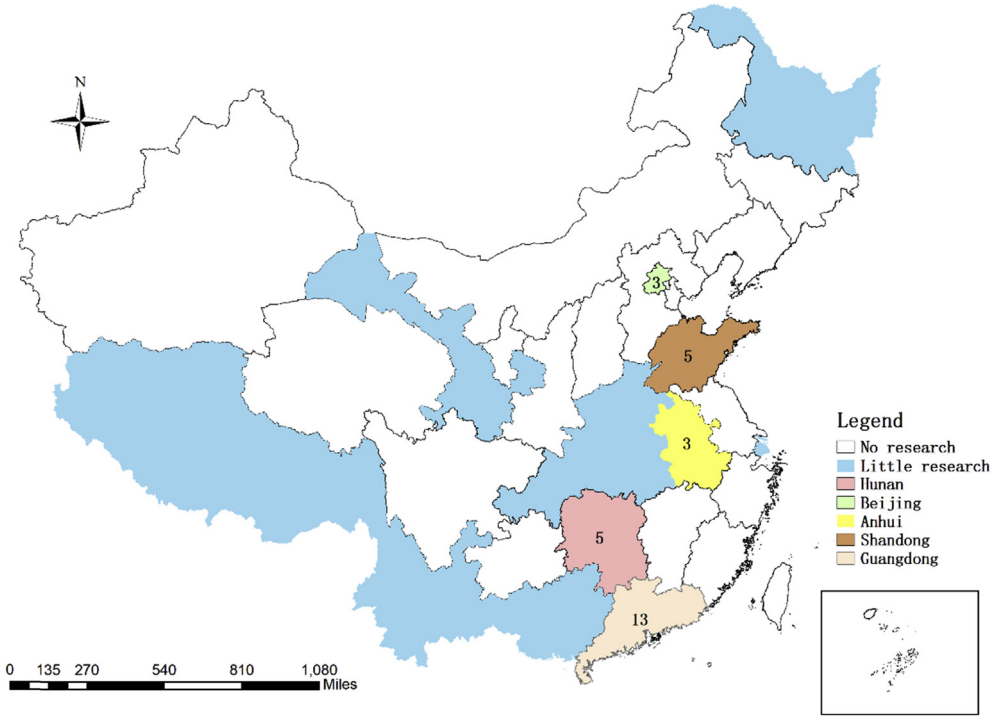

Fig. 2. Research locations across China.

3.3.2.2. Schistosomiasis. In China, the geographical distribution of the snail host *O. hupensis* is restricted to areas where the mean January temperature is above 0 °C (Wang et al., 2014a). The environmental conditions such as temperature, precipitation and humidity were reported to directly or indirectly influence the living habit of intermediate host snails and schistosome eggs, larvae and adults thus alter the transmission of schistosomiasis (Wei et al., 2013; Lv and Lin, 2014; Cook, 1992). Zhou found a temperature threshold of 15.4 °C for the development of Schistosoma japonicum within the *Oncomelania hupensis* and a temperature of 5.8 °C at which half the snail sample investigated was in hibernation (Zhou et al., 2008; Yang et al., 2006). It has been predicted that a northward expansion of transmission area of schistosomiasis may occur due to the climate warming, with an additional 783,883 km^2 area, and 20.7 million people at risk of infection by 2050 (Zhou et al., 2004, 2008; Yang et al., 2005). In eastern China, the mean T_{min} −4 °C in January is the boundary line between the epidemic area and the non-endemic area, which suggests that the frozen environment plays a major role in hindering the migration of schistosomiasis to the north (Zhou et al., 1999). In addition, the differences of the subspecies of *O. hupensis* are worth studying and comparing in a climate change context (Zhu et al., 2017). The application of geographic information system (GIS) technology and the ecological niche modeling (ENM) may have play a significant role in predicting the prevalence of schistosomiasis in China (Zhu et al., 2017). (Table A.3)

3.3.3. Viral infectious disease

3.3.3.1. Dengue. Dengue fever, a viral disease, is the fastest increasing vector-borne disease in the world with only one thousand cases reported in the 1950s to more than 90 million cases in the 2000s (Sang et al., 2015). In 2014, a major outbreak occurred in Guangzhou city, southern China, causing significant public health problem, with about 50,000 cases (Xiang et al., 2017). As the climate gets warmer, there has been a trend of expanded geographical region for dengue infections, from South to North China (Li et al., 2017). Many investigations studied the association between climatic factors and dengue incidence using various analytical approaches controlling for confounders. For example, a study in Guangzhou pointed out that the optimal T_{max} range for dengue transmission was 21.6 °C–32.9 °C, and 11.2 °C–23.7 °C for T_{min} (Xiang et al., 2017). Gu (Gu et al., 2016) concluded that temperature contributed most to the risk for dengue fever in South China while other research reported that precipitation variables played a more important role than temperature in similar regions (Sang et al., 2014; Cheng et al., 2016), suggesting more research is needed. Wang (Wang et al., 2014b) found that dengue incidences were positively associated with relative humidity and temperature, and negatively with wind velocity and precipitation in southern China, which was inconsistent with other results (Zhang et al., 2016a). The identification of threshold temperature and lag effects can be helpful for dengue control and prevention in dengue epidemic areas (Li et al., 2014a; Tong et al., 2016) (Table A.4).

3.3.3.2. HFMD. Transmitted by close contact, HFMD is an acute infectious disease caused by a group of enteroviruses, of which *Coxsackie virus A 16* and *Enterovirus 71* are two major agents (Huang et al., 2016; Li et al., 2014b; Yang et al., 2015). The incidence of HFMD is one of the major causes of death among children in China (Xu et al., 2015; Jiang et al., 2016). Seasonal distribution of HFMD suggested that climatic factors might affect the disease transmission. Average temperature, relative humidity and wind speed were found positively associated, while daily precipitation and sunshine hours were negatively associated with HFMD incidence in Gansu (Northwest), Shanghai (East), Chongqing (Southwest) (Qi et al., 2018; Wang et al., 2017; Gou et al., 2018) while observations in some other areas show contradictory results (Wu et al., 2017b), indicating the local climatic characteristics, socioeconomic status and behavior factors may contribute to the disease transmission. Zhu (Zhu et al., 2016) concluded that within a suitable range, the higher the temperature is, the higher the morbidity is, which is consistent with the findings from Qi (Qi et al., 2018) and Dong (Dong et al., 2016). A research conducted in Gansu Province using generalized linear regression models revealed an increase in weekly HFMD of 1.8%–5.9% in association with 1 °C increase in mean temperature (Gou et al., 2018). A study in Anhui Province, eastern China, found that extreme precipitation was

significantly associated with HFMD (Cheng et al., 2014). The threshold points for temperature for HFMD transmission in western China ranged from 16 °C to 20 °C (Gou et al., 2018). Taking the incubation of HFMD (3–7 days) into account, the lag effects of temperature, relative humidity, and extreme precipitation were identified, which may provide implications for HFMD early warning system (Wang et al., 2017; Zhang et al., 2015, 2016b; Wei et al., 2015) (Table A.5).

3.3.3.3. HFRS. HFRS, also known as epidemic hemorrhagic fever, is a zoonosis caused by different species of Hanta-viruses transmitted by rodents (Bi et al., 1998). Widely prevalent in China, a total of 68,069 HFRS cases were reported and 466 people died over the period 2012 to 2017 (Chinese center for disease control and prevention, 2018). Climatic factors may influence the crop growth, ecological environment and mice density, as well as human activity, then the incidence rate of HFRS (Bi et al., 2005a). Given the range of climate zones and geographical and agricultural characteristics, the influences of precipitation, temperature and humidity on HFRS incidence have been found varied. The relative humidity, precipitation, and mean temperature were found to be negatively correlated with the monthly number of HFRS cases, while the effect of wind velocity had a positive correlation in East and North China (Bi et al., 2005a; Liu et al., 2011). Other related studies have also demonstrated the average humidity influencing factor shows positive associated with HFRS cases (Ge et al., 2016). SOI (Southern Oscillation Index) has been used as an index across a large geographical area (Bi et al., 1998, 2005b). Based on 22-years data, an inverse relationship between the SOI and the monthly incidence of HFRS was found in Anhui Province (Bi et al., 2005b), consistent with a study in Heilongjiang Province (Bi et al., 1998). Recent years, vaccination programs and rodent control measures have been taken which contributed to the decrease of the disease substantially (Hansen et al., 2015). However more work is still needed to better quantify the influence of climatic variables, taking into account the impact of landscape, and develop prevention guidelines for high-risk groups (Table A.6).

3.3.3.4. JE. Japanese Encephalitis, also known as epidemic encephalitis B, is a major mosquito-borne infectious disease caused by Japanese encephalitis virus with pigs as reservoir host and the source of infection (Tian et al., 2015). It can occur throughout the year in tropical regions, but with seasonal distribution in subtropical and temperate regions suggesting that the climatic variables may play a certain role in its transmission. Studies in different regions have indicated that monthly (Bai et al., 2014b; Bi et al., 2007; Wang et al., 2014c)or daily (Zhang et al., 2016c) climatic variables can affect the epidemiology of JE through affecting the mosquito life cycle, virus ecology, human behavior thus virus-human interaction (Bai et al., 2014b). Temperature was found to be closely associated with mosquito density and JE incidence (Bai et al., 2014b; Bi et al., 2007; Zhang et al., 2016c). A study conducted in Chongqing, southwestern China, reported that JE incidence peaked in the years that there was a higher temperature (Bai et al., 2014b). The Hockey Stick model detected the threshold temperature for JE transmission, with maximum of 25.2 °C and minimum temperature of 21.0 °C in Jinan city, Eastern China (Bi et al., 2007). Using the ZIPR model, Bai found a negative association between the precipitation and JE incidence (Bai et al., 2014b). In addition, Wang (Wang et al., 2014c) found that JE cases were positively associated with relative humidity. A recent study also showed the positive effect of floods on notified cases of Japanese encephalitis (Zhang et al., 2016c). (Table A.7)

3.4. Further directions for climate change and infectious disease transmission study in China

3.4.1. Lagged effect

The temperature increase in the southern China is higher than that in the northern part, which seems consistent with the distribution of infectious diseases. Additionally, a series of time-series analyses found the temperature lag effect in southern cities was shorter than that in northern parts indicating that impact of climate change on infectious disease transmission might be more obvious in southern cities of China (Zhang et al., 2008; Li et al., 2015). More studies are needed to confirm this finding, and relevant actions and preventative measurements should be established to protect population health, especially those vulnerable populations.

3.4.2. More comprehensive studies are needed

Most published articles mainly worked at the local level with a limited timeframe. A meta-analysis with multiple-locations with similar climatic characteristics over a long study period will provide a stronger evidence for scientific community (Xiang et al., 2018a, 2018b; Gao et al., 2012; Tong et al., 2015). The China National infectious disease surveillance system provides an excellent platform for such initiative. A better data sharing mechanism across sectors and data custodians will promote such collaborations.

3.4.3. Burden of infectious diseases due to climate change

It is important to understand the burdens of infectious diseases to the health system in China, especially those could be attributed to climate change in future so relevant health resource planning and allocation can be arranged. Unfortunately, there have been very few studies in this area and more work is needed.

3.4.4. Data analytic approach

Most of the published studies used an ecological study design for the time-series data. In terms of time-series data analyses, various statistical methods and mathematical models were implemented. The DLNM and SARIMA model were the most commonly used approaches. The Hockey-Stick model might provide a tool for each region to detect its own threshold temperature for early warning purpose. More scientific statistical methods and mathematical models are expected to be explored.

3.4.5. Infectious disease adaptation strategy in the context of climate change

Climate change will continue to impact the transmission of infectious diseases so relevant adaptation strategies are needed. Such initiatives could examine the current capacity in the healthcare system to deal with such challenges, including healthcare workforce, resource and facility, policy and guidelines, as well as the community demands, to reduce the burdens of infectious diseases to the health system.

4. Conclusions

Many infectious diseases such as malaria, schistosomiasis, dengue fever and other vector-borne diseases are most affected by climate variability and climate change. Exploring the health effects from climatic factors can assist health authorities to develop relevant preventative and adaptive mechanism, implement early warning systems, especially in the context of climate change. More research is needed to further investigate the characterization of climate–infectious diseases associations in different climatic zones; to detect thresholds of meteorological factors for early warning purposes; to identify and to protect vulnerable populations, and to explore adaptation strategies to deal with the various infectious disease challenges that result from climate change.

Conflicts of interest

The authors declare that they have no competing interests.

Authors' contributions

JL, PB and QL initiated the study. LY, XX and WG collected the references. HX, JL, DL and CW selected the references. LY, XX and WG drafted the manuscript. HW, XL, DZ and ZC provided significant intellectual advice. JL, PB, QL and XX revised the manuscript. All authors read and approved the final manuscript.

Acknowledgements

This study was supported by the Social Science Planning Research Project of Shandong Province (18CQXJ18), Medicine and Health of Shandong Province for Science and Technology Development Program (2017WS703, 2016WS0664), State Key Laboratory of Infectious Disease Prevention and Control Program of China (2018SKLID306), and the National Natural Science Foundation of China (81703280). We appreciated the anonymous reviewers very much, whose insightful and suggestions contributed a lot to improving the quality of our manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2019.03.043.

Funding

This study was supported by the Social Science Planning Research Project of Shandong Province (18CQXJ18), Medicine and Health of Shandong Province for Science and Technology Development Program (2017WS703, 2016WS0664), Science and Technology Project of Shandong Health Science and Technology Association, State Key Laboratory of Infectious Disease Prevention and Control Program of China (2018SKLID306), and the National Natural Science Foundation of China (81703280).

References

Bai, L., Morton, L.C., Liu, Q., 2013. Climate change and mosquito-borne diseases in China: a review. Glob. Health 9 (1), 1–22.

Bai, L., Ding, G., Gu, S., Bi, P., Su, B., Qin, D., Xu, G., Liu, Q., 2014a. The effects of summer temperature and heat waves on heat-related illness in a coastal city of China, 2011–2013. Environ. Res. 132, 212–219.

Bai, Y., Xu, Z., Zhang, J., Mao, D., Luo, C., He, Y., Liang, G., Lu, B., Bisesi, M.S., Sun, Q., 2014b. Regional impact of climate on Japanese encephalitis in areas located near the three gorges dam. PLoS One 9 (1), e84326.

Bi, P., Wu, X., Zhang, F., Parton, K.A., Tong, S., 1998. Seasonal rainfall variability, the incidence of hemorrhagic fever with renal syndrome, and prediction of the disease in low-lying areas of China. Am. J. Epidemiol. 148 (3), 276–281.

Bi, P., Parton, K.A., Tong, S., 2005a. El nino-southern oscillation and vector-borne diseases in Anhui, China. Vector Borne Zoonotic Dis. 5 (2), 95–100.

Bi, P., Parton, K.A., Tong, S., 2005b. El nino-southern oscillation and vector-borne diseases in Anhui, China. Vector Borne Zoonotic Dis. 5 (2), 95.

Bi, P., Zhang, Y., Parton, K.A., 2007. Weather variables and Japanese encephalitis in the metropolitan area of Jinan city, China. J. Infect. 55 (6), 551–556.

Bi, Y., Yu, W., Hu, W., Lin, H., Guo, Y., Zhou, X.N., Tong, S., 2013. Impact of climate variability on Plasmodium vivax and Plasmodium falciparum malaria in Yunnan province, China. Parasites Vectors 6 (1), 1–12.

Cheng, J., Wu, J., Xu, Z., Zhu, R., Wang, X., Li, K., Wen, L., Yang, H., Su, H., 2014. Associations between extreme precipitation and childhood hand, foot and mouth disease in urban and rural areas in Hefei, China. Sci. Total Environ. 484, 497–498.

Cheng, Q., Jing, Q., Spear, R.C., Marshall, J.M., Yang, Z., Peng, G., 2016. Climate and the timing of imported cases as determinants of the dengue outbreak in Guangzhou, 2014: evidence from a mathematical model. PLoS Neglected Trop. Dis. 10 (2), e0004417.

Chinese center for disease control and prevention National notifiable infectious diseases epidemic situation. Available at: http://www.chinacdc.cn/ , Accessed date: 26 February 2018.

Cook, G.C., 1992. Effect of global warming on the distribution of parasitic and other infectious diseases: a review. J. R. Soc. Med. 85 (11), 688.

Dong, W., Li, X.E., Yang, P., Liao, H., Wang, X., Wang, Q., 2016. The effects of weather factors on hand, foot and mouth disease in Beijing. Sci. Rep. 6, 19247.

Gao, H.W., Wang, L.P., Song, L., Liu, Y.X., Tong, S.L., Wang, J.J., Li, Y.P., Wang, X.F., Hong, Y., Ma, J.Q., 2012. Change in rainfall drives malaria Re-emergence in Anhui province, China. PLoS One 7 (8), e43686.

Gao, L., Zhang, Y., Ding, G., Liu, Q., Zhou, M., Li, X., Jiang, B., 2014. Meteorological variables and bacillary dysentery cases in Changsha city, China. Am. J. Trop. Med. Hyg. 90 (4), 697–704.

Gao, L., Zhang, Y., Ding, G., Liu, Q., Jiang, B., 2016. Identifying flood-related infectious diseases in Anhui province, China: a spatial and temporal analysis. Am. J. Trop. Med. Hyg. 94 (4), 741–749.

Ge, L., Zhao, Y., Zhou, K., Mu, X., Yu, H., Wang, Y., Wang, N., Fan, H., Guo, L., Huo, X.X., 2016. Spatio-temporal pattern and influencing factors of hemorrhagic fever with renal syndrome (HFRS) in Hubei province (China) between 2005 and 2014. PLoS One 11 (12), e0167836.

Gou, F., Liu, X., He, J., Liu, D., Cheng, Y., Liu, H., Yang, X., Wei, K., Zheng, Y., Jiang, X., 2018. Different responses of weather factors on hand, foot and mouth disease in three different climate areas of Gansu, China. BMC Infect. Dis. 18 (1), 15.

Gu, H., Ka-Kit, L.R., Jing, Q., Zhang, W., Yang, Z., Lu, J., Hao, Y., Zhang, D., 2016. Meteorological factors for dengue fever control and prevention in south China. Int. J. Environ. Res. Public Health 13 (9), 867.

Guo, C., Yang, L., Ou, C.Q., Li, L., Zhuang, Y., Yang, J., Zhou, Y.X., Qian, J., Chen, P.Y., Liu, Q.Y., 2015. Malaria incidence from 2005-2013 and its associations with meteorological factors in Guangdong, China. Malar. J. 14 (1), 116.

Hansen, A., Cameron, S., Liu, Q., Sun, Y., Weinstein, P., Williams, C., Han, G.S., Bi, P., 2015. Transmission of haemorrhagic fever with renal syndrome in China and the role of climate factors: a review. Int. J. Infect. Dis. 33, 212–218.

Heaney, A., Little, E., Ng, S., Shaman, J., 2016. Meteorological variability and infectious disease in Central Africa: a review of meteorological data quality. Ann. N. Y. Acad. Sci. 1382 (1), 31–43.

Huang, D., Peng, G., Guo, J., Ping, W., Zhou, B., 2008. Investigating the effects of climate variations on bacillary dysentery incidence in northeast China using ridge regression and hierarchical cluster analysis. BMC Infect. Dis. 8 (1), 130.

Huang, F., Zhou, S., Zhang, S., Wang, H., Tang, L., 2011. Temporal correlation analysis between malaria and meteorological factors in Motuo County, Tibet. Malar. J. 10 (1), 54.

Huang, R., Bian, G., He, T., Lv, C., Xu, G., 2016. Effects of meteorological parameters and PM10 on the incidence of hand, foot, and mouth disease in children in China. Int. J. Environ. Res. Public Health 13 (5), 481.

Huang, Q., Hu, L., Liao, Q.B., Xia, J., Wang, Q.R., Peng, H.J., 2017. Spatiotemporal analysis of the malaria epidemic in mainland China, 2004-2014. Am. J. Trop. Med. Hyg. 97 (2), 504.

Jiang, F.C., Yang, F., Chen, L., Jia, J., Han, Y.L., Hao, B., Cao, G.W., 2016. Meteorological factors affect the hand, foot, and mouth disease epidemic in Qingdao, China, 2007-2014. Epidemiol. Infect. 144 (11), 1–9.

Kan, H., Chen, R., Tong, S., 2012. Ambient air pollution, climate change, and population health in China. Environ. Int. 42 (1), 10–19.

Lan, L., Hong, R., 2013. Infectious Diseases. People's Health Publishing House, BeiJing, pp. 178–183.

Li, Z., Wang, L., Sun, W., Hou, X., Yang, H., Sun, L., Xu, S., Sun, Q., Zhang, J., Song, H., 2013a. Identifying high-risk areas of bacillary dysentery and associated meteorological factors in Wuhan, China. Sci. Rep. 3 (7476), 3239.

Li, T., Yang, Z., Wang, M., 2013b. Temperature, relative humidity and sunshine may be the effective predictors for occurrence of malaria in Guangzhou, southern China, 2006-2012. Parasites Vectors 6 (1), 155.

Li, T., Yang, Z., Wang, M., 2014a. Temperature and atmospheric pressure may be considered as predictors for the occurrence of bacillary dysentery in Guangzhou, Southern China. Rev. Soc. Bras. Med. Trop. 47 (3), 382–384.

Li, T., Yang, Z., Liu, X., Kang, Y., Wang, M., 2014b. Hand-foot-and-mouth disease epidemiological status and relationship with meteorological variables in Guangzhou, Southern China, 2008-2012. Rev. Inst. Med. Trop. Sao. Paulo. 56 (6), 533–539.

Li, Z.J., Zhang, X.J., Hou, X.X., Xu, S., Zhang, J.S., Song, H.B., Lin, H.L., 2015. Nonlinear and threshold of the association between meteorological factors and bacillary dysentery in Beijing, China. Epidemiol. Infect. 143 (16), 3510–3519.

Li, C., Lu, Y., Liu, J., Wu, X., 2017. Climate change and dengue fever transmission in China: evidences and challenges. Sci. Total Environ. 622–623, 493.

Liang, L., Gong, P., 2017. Climate change and human infectious diseases: a synthesis of research findings from global and spatio-temporal perspectives. Environ. Int. 103, 99–108.

Liu, X., Jiang, B., Gu, W., Liu, Q., 2011. Temporal trend and climate factors of hemorrhagic fever with renal syndrome epidemic in Shenyang City, China. BMC Infect. Dis. 11 (1), 331.

Lv, S.B., Lin, D.D., 2014. Natural environment and schistosomiasis transmission in Poyang Lake region. Chin. J. Schistosomiasis Control 26 (5), 561.

National Bureau of Statistics Statistical communiqué of the People's Republic of China on 2017 national economic and social development. Available at: http://www.stats.gov.cn/ , Accessed date: 28 February 2018.

Qi, H., Chen, Y., Xu, D., Su, H., Zhan, L., Xu, Z., Huang, Y., He, Q., Hu, Y., Lynn, H., 2018. Impact of meteorological factors on the incidence of childhood hand, foot, and mouth disease (HFMD) analyzed by DLNMs-based time series approach. Infect. Dis. Poverty 7 (1), 7.

Ren, Z., Wang, D., Ma, A., Hwang, J., Bennett, A., Sturrock, H.J.W., Fan, J., Zhang, W., Yang, D., Feng, X., 2016. Predicting malaria vector distribution under climate change scenarios in China: challenges for malaria elimination. Sci. Rep. 6 (6), 20604.

Sang, S., Yin, W., Bi, P., Zhang, H., Wang, C., Liu, X., Chen, B., Yang, W., Liu, Q., 2014. Predicting local dengue transmission in Guangzhou, China, through the influence of imported cases, mosquito density and climate variability. PLoS One 9 (7), e102755.

Sang, S., Gu, S., Bi, P., Yang, W., Yang, Z., Xu, L., Yang, J., Liu, X., Jiang, T., Wu, H., 2015. Predicting unprecedented dengue outbreak using imported cases and climatic factors in Guangzhou, 2014. PLoS Neglected Trop. Dis. 9 (5) e0003808.

Shuman, E.K., 2011. Global climate change and infectious diseases. Int. J. Occup. Environ. Med. 2 (1), 11–19.
Song, Y., Ge, Y., Wang, J., Ren, Z., Liao, Y., Peng, J., 2016. Spatial distribution estimation of malaria in northern China and its scenarios in 2020, 2030, 2040 and 2050. Malar. J. 15 (1), 345.
Tian, H.Y., Bi, P., Cazelles, B., Zhou, S., Huang, S.Q., Yang, J., Pei, Y., Wu, X.X., Fu, S.H., Tong, S.L., 2015. How environmental conditions impact mosquito ecology and Japanese encephalitis: an eco-epidemiological approach. Environ. Int. 79, 17–24.
Tong, M.X., Hansen, A., Hansoneasey, S., Cameron, S., Xiang, J., Liu, Q., Sun, Y., Weinstein, P., Han, G.S., Williams, C., 2015. Infectious diseases, urbanization and climate change: challenges in future China. Int. J. Environ. Res. Public Health 12 (9), 11025–11036.
Tong, M.X., Hansen, A., Hanson-Easey, S., Xiang, J., Cameron, S., Liu, Q., Liu, X., Sun, Y., Weinstein, P., Han, G.S., 2016. Perceptions of capacity for infectious disease control and prevention to meet the challenges of dengue fever in the face of climate change: a survey among CDC staff in Guangdong province, China. Environ. Res. 148, 295–302.
Wang, W., Dai, J.R., Liang, Y.S., 2014a. Apropos: factors impacting on progress towards elimination of transmission of schistosomiasis japonica in China. Parasites Vectors 7 (1), 408.
Wang, C., Jiang, B., Fan, J., Wang, F., Liu, Q., 2014b. A study of the dengue epidemic and meteorological factors in Guangzhou, China, by using a zero-inflated Poisson regression model. Asia Pac. J. Public Health 26 (1), 48–57.
Wang, L., Hu, W., Soares Magalhaes, R.J., Bi, P., Ding, F., Sun, H., Li, S., Yin, W., Wei, L., Liu, Q., 2014c. The role of environmental factors in the spatial distribution of Japanese encephalitis in Mainland China. Environ. Int. 73, 1–9.
Wang, P., Zhao, H., You, F., Zhou, H., Goggins, W.B., 2017. Seasonal modeling of hand, foot, and mouth disease as a function of meteorological variations in Chongqing, China. Int. J. Biometeorol. 61 (8), 1–9.
Wei, W., Liang, Y.S., Hong, Q.B., Dai, J.R., 2013. African schistosomiasis in mainland China: risk of transmission and countermeasures to tackle the risk. Parasites Vectors 6 (1), 1–6.
Wei, J., Hansen, A., Liu, Q., Sun, Y., Weinstein, P., Bi, P., 2015. The effect of meteorological variables on the transmission of hand, foot and mouth disease in four major cities of shanxi province, China: a time series data analysis (2009-2013). PLoS Neglected Trop. Dis. 9 (3), e0003572.
World Health Organization Climate change. Available at: http://www.who.int/topics/climate/en , Accessed date: 11 October 2010.
Wu, Y., Qiao, Z., Wang, N., Yu, H., Feng, Z., Li, X., Zhao, X., 2017a. Describing interaction effect between lagged rainfalls on malaria: an epidemiological study in south-west China. Malar. J. 16 (1), 53.
Wu, X., Hu, S., Kwaku, A.B., Li, Q., Luo, K., Zhou, Y., Tan, H., 2017b. Spatio-temporal clustering analysis and its determinants of hand, foot and mouth disease in Hunan, China, 2009-2015. BMC Infect. Dis. 17 (1), 645.
Xiang, J., Hansen, A., Liu, Q., Liu, X., Tong, M.X., Sun, Y., Cameron, S., Hanson-Easey, S., Han, G.S., Williams, C., 2017. Association between dengue fever incidence and meteorological factors in Guangzhou, China, 2005–2014. Environ. Res. 153, 17–26.
Xiang, J., Hansen, A., Liu, Q., Tong, M.X., Liu, X., Sun, Y., Cameron, S., Hanson-easey, S., Han, G.S., Williams, C., Weinstein, P., Bi, P., 2018a. Association between malaria incidence and meteorological factors: a multi-location study in China, 2005-2012. Epidemiol. Infect. 146 (1), 89–99.
Xiang, J., Hansen, A., Liu, Q., Tong, M.X., Liu, X., Sun, Y., Cameron, S., Hansoneasey, S., Han, G.S., Williams, C., 2018b. Impact of meteorological factors on hemorrhagic fever with renal syndrome in 19 cities in China, 2005-2014. Sci. Total Environ. 636, 1249–1256.
Xu, M., Yu, W., Tong, S., Jia, L., Liang, F., Pan, X., 2015. Non-linear association between exposure to ambient temperature and children's hand-foot-and-mouth disease in Beijing, China. PLoS One 10 (5), e0126171.
Yan, L., Wang, H., Zhang, X., Li, M.Y., He, J., 2017. Impact of meteorological factors on the incidence of bacillary dysentery in Beijing, China: a time series analysis (1970-2012). PLoS One 12 (8), e0182937.
Yang, G.J., Vounatsou, P., Zhou, X.N., Tanner, M., Utzinger, J., 2005. A potential impact of climate change and water resource development on the transmission of Schistosoma japonicum in China. Parassitologia 47 (1), 127.
Yang, G.J., Gemperli, A., Vounatsou, P., Tanner, M., Zhou, X.N., Utzinger, J., 2006. A growing degree-days based time-series analysis for prediction of Schistosoma japonicum transmission in Jiangsu province, China. Am. J. Trop. Med. Hyg. 75 (3), 549–555.
Yang, H., Wu, J., Cheng, J., Wang, X., Wen, L., Li, K., Su, H., 2015. Is high relative humidity associated with childhood hand,foot,and mouth disease in rural and urban areas? Publ. Health 142, 201.
Zhang, Y., Bi, P., Hiller, J.E., Sun, Y., Ryan, P., 2007. Climate variations and bacillary dysentery in northern and southern cities of China. J. Infect. 55 (2), 194–200.
Zhang, Y., Bi, P., Hiller, J.E., 2008. Weather and the transmission of bacillary dysentery in Jinan, northern China: a time-series analysis. Publ. Health Rep. 123 (1), 61–66.
Zhang, Y., Bi, P., Hiller, J.E., 2010. Meteorological variables and malaria in a Chinese temperate city: a twenty-year time-series data analysis. Environ. Int. 36 (5), 439–445.
Zhang, W., Du, Z., Zhang, D., Yu, S., Hao, Y., 2015. Quantifying the adverse effect of excessive heat on children: an elevated risk of hand, foot and mouth disease in hot days. Sci. Total Environ. 541, 194–199.
Zhang, Y., Tao, W., Liu, K., Yao, X., Yi, L., Jing, Q., Yang, Z., Hu, W., Lu, J., 2016a. Developing a time series predictive model for dengue in Zhongshan, China based on weather and Guangzhou dengue surveillance data. PLoS Neglected Trop. Dis. 10 (2), e0004473.
Zhang, W., Du, Z., Zhang, D., Yu, S., Hao, Y., 2016b. Boosted regression tree model-based assessment of the impacts of meteorological drivers of hand, foot and mouth disease in Guangdong, China. Sci. Total Environ. 553, 366–371.
Zhang, F., Liu, Z., Zhang, C., Jiang, B., 2016c. Short-term effects of floods on Japanese encephalitis in Nanchong, China, 2007–2012: a time-stratified case-crossover study. Sci. Total Environ. 563–564, 1105–1110.
Zhou, X., Hu, X., Sun, N., Hong, Q., Sun, L., Lu, G., Fuentes, M., Maone, J.B., 1999. Application of geographic information systems on schistosomiasis surveillance–II.-predicting transmission intensity. Chin. J. Schistosomiasis Control (02), 66–70.
Zhou, X.N., Yang, K., Hong, Q.B., Sun, L.P., Yang, G.J., Liang, Y.S., Huang, Y.X., 2004. Prediction of the impact of climate warming on transmission of schistosomiasis in China. Chin. J. Parasitol. Parasit. Dis. 22 (5), 262–265.
Zhou, X.N., Yang, G.J., Yang, K., Wang, X.H., Hong, Q.B., Sun, L.P., Malone, J.B., Kristensen, T.K., Bergquist, N.R., Utzinger, J., 2008. Potential impact of climate change on schistosomiasis transmission in China. Am. J. Trop. Med. Hyg. 78 (2), 188–194.
Zhu, L., Wang, X., Guo, Y., Xu, J., Xue, F., Liu, Y., 2016. Assessment of temperature effect on childhood hand, foot and mouth disease incidence (0-5years) and associated effect modifiers: a 17 cities study in Shandong Province, China, 2007-2012. Sci. Total Environ. 452, 551–552.
Zhu, G., Fan, J., Peterson, A.T., 2017. Schistosoma japonicumtransmission risk maps at present and under climate change in mainland China. PLoS Neglected Trop. Dis. 11 (10) e0006021.